Additive Manufacturing

From Form to Function

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We might possess every technological resource . . . but if our language is inadequate, our vision remains formless, our thinking and feeling are still running in the old cycles, our process may be "revolutionary" but not transformative.

—Adrienne Rich, poet

Abstract

This article explores the status and opportunity space of additive manufacturing (AM) for defense efforts, while explaining its shaping for multidomain (land, air, maritime, space, and cyberspace) applications through strategic and operational agility. As an efficient tool for design reiteration and rapid prototyping, AM is changing the landscape of the US manufacturing base. Technological advances in the private sector are being implemented into national defense efforts, including investment in a National Network for Manufacturing Innovation (NNMI). However, for AM to be considered a "game changing technology," increases in functionality of the fundamental building-block materials and printer configurations are needed to enable the most revolutionary applications. Simply put, the vision is to move additive manufacturing technology from form to function. In this way, AM can be increasingly used in military mission areas such as logistics, sustainment, and modular weapons development.

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The concept of strategic agility is defined by the attributes of flexibility, adaptability, and speed, thereby providing an answer to the challenge of rapid, unexpected change.[1] Similarly, operational agility—defined by the rapid generation of solutions and the ability to shift among multiple solutions for a given challenge—provides an answer to emerging threats.[2] AM fits into plans for both strategic and operational agility.[3] It is a potential game-changing technology that can maximize multidomain (land, air, maritime, space, and cyberspace) integration, which provides great flexibility.[4] The reality is that the defense challenges of the twenty-first century cannot be resolved with a single answer but require agility to offer many answers. The rapid pace of change can clearly be seen as an impediment to those unable to adapt, but it also becomes an enduring advantage to the agile.[5] While we may not always need to operate at the fastest speed possible, the option to do so reduces an adversary's opportunity to react.[6] AM enables agility by providing fast and inexpensive design and the manufacture of single or multiple prototypes to meet a range of mission needs, including instant part repair and replacement in the field.[7] The ability to place printers and materials in various strategic locations—including land, sea, and space—provides options for on-demand product production to reduce manufacturing cycle times in the design and assembly phases. There is a strong case that AM holds the potential to support many facets of the US defense mission while providing long-term cost savings.[8]

The goal of this article is to provide an awareness and perspective for future joint efforts by exploring the status and shaping of AM capabilities through the strategic framework contained within key US Air Force (USAF) reports, planning documents, and other relevant resources. While this effort focuses on USAF examples, the concept of AM can apply to all Department of Defense (DOD) services and agencies. The article begins by exploring the growth of AM within the military and then ventures into the role of AM in logistics and sustainment. Next, it assesses the impact of AM on the acquisition process and concludes with future opportunities and challenges of AM.

Growth of AM in the Military

The United States is undergoing an intense reinvigoration of its industrial manufacturing base to harness the effective design reiteration and rapid prototyping capabilities afforded by AM. For example, accord-

ing to the *Wohlers Report 2015*, the AM industry has seen tremendous growth since 1995 when it was a $295 million endeavor to a projected $4.1 billion market in 2014. The number of industrial 3D printer manufacturers has more than tripled since 1995 when there were only 15. There are now 49 companies in 13 countries, selling more than 12,850 systems valued from $5,000 to upwards of $500,000 each. The dominant industrial sectors that utilize AM in order of greatest to least include industrial/business machines (17.5 percent), consumer products/electronics (16.6 percent), motor vehicles (16.1 percent), aerospace (14.8 percent), medical/dental (13.1 percent), academic institutions (8.2 percent), government/military (6.6 percent), "other" such as oil, gas, and commercial products (3.9 percent), and architectural (3.2 percent). Although the percentage for government/military use of AM is summarized as only 6.6 percent, according to the *Wohlers Report 2015*, this is a 1.2 percent growth from the previous data in 2014.[9]

Each of the military branches, as well as most of the depots and arsenals, are conducting independent AM development efforts and projects.[10] For example, 3D printers have been deployed into "the field" by the Army, Navy, and DOD contractors from 2012–2014 and continue to be incorporated into new exploratory efforts.[11] There are also significant collaborations across the services, all of which have been initiated or strengthened in the past two years as investments continue to grow.

AM Research and Development for Military Applications

For multidomain effects to be realized, the Air Force Research Laboratory (AFRL) Munitions Directorate at Eglin AFB, Florida, is working in close collaboration with the Materials and Manufacturing Directorate and Sensors Directorate at Wright Patterson AFB, Ohio, to adapt AM into applications such as flexible, modular weapons for limited bay space, changing targets, conformal information systems research, and flexible electronics. The maturation of AM in these target areas will fuel capabilities to increase the lethality of small weapons and decrease the time and cost it takes to refresh critical components.[12]

The Flexible Electronics and General Ordnance Manufacturing (FLEGOMAN) program took a holistic approach to develop AM for multiple parts and materials incorporated into a representative munition, including metallic casings, novel conductive "inks" for electronic

traces and capacitors, and modified energetic material formulations compatible with printing. Some of the benefits of directly printing electronics include using space more efficiently than conventionally-made electronics and generating less waste. For example, simplifying electronics into printed patterns on the interior or exterior of weapon systems could allow size and weight reductions and free up valuable internal space. Other examples of printing flexible electronics include radio antennas on soldiers' helmets that could reduce weight and enhance mobility and embedded electronics in clothing that could allow additional protective benefits and health monitoring options.[13]

AM has also enabled proof-of-concept design of subscale penetrators at the Air Force Institute of Technology (AFIT). The novel designs included intricate internal cellular features that are not possible with traditional subtractive manufacturing techniques. A method known as *topology optimization* was incorporated into the design process to generate strategic trusses optimized for stress distribution, which reduces the overall weight of the structure. Further refinements in the metal compositions and post-processing heat treatments to increase strength are under way.[14]

AM detonators have been developed under the FLEGOMAN program in collaboration with the Army's Armament Research, Development and Engineering Center (ARDEC) at Picatinny Arsenal, New Jersey. Indeed, electronic printing is at the forefront of Picatinny Arsenal's research, including inkjet- and screen-printing munitions antennas, fuze elements (such as exploding foil initiators), and batteries.[15] The use of AM techniques has enabled a host of nontraditional, but highly promising, material options to be pursued, including metallic nanoparticles. These novel manufacturing techniques and materials have the potential to surpass the performance of traditionally manufactured devices while enjoying the logistical flexibility afforded by AM.

The Army Aviation and Missile Research Development and Engineering Center (AMRDEC) in Huntsville, Alabama, is developing tools and processes to advance the state of topology optimization for missile structures and components. Topology optimization is a design process used to generate structures that use minimal material to perform a desired function, such as maximized stiffness, tailored natural frequency, and optimized heat flow. The AMRDEC programs will streamline the optimization/design process, improve lightweight cellular structures, incorporate fabrication considerations, and demonstrate optimized missile

structures. AMRDEC science and technology programs are in collaboration with Materials Sciences Corporation in Horsham, Pennsylvania; the Sandia National Laboratories; and the University of Pittsburgh. The AMRDEC will stand up a new AM facility in 2017 to accommodate these programs, train AMRDEC personnel, and advance the state of AM for aviation and missile applications.

The Navy has also been taking advantage of the recent surge in AM. As an early adopter, it has used generations of AM technologies for the last 20 years to assist in prototype development. But in the past few years, the Navy has explored AM as a means to overcome the obsolescence of parts. Too often a part produced during the development of a family of ships or submarines is no longer produced by the original manufacturer or the manufacturer no longer exists, leading to costly and long acquisition processes that could leave a ship stuck in port. At the Navy's fleet readiness centers and regional maintenance centers, AM is being used in many different ways to save time and money for the benefit of fleet readiness.[16] As mentioned earlier, the Navy's desire to improve readiness is being tested at sea.[17] To enable AM to produce drop-in parts instead of only prototypes, the Navy's Office of Naval Research has been reaching out to industry. Such partnerships are essential in ensuring that AM-produced parts can meet material and fleet requirements.[18] The Navy weapons' enterprise also seeks to adopt AM as a means of addressing a shrinking American manufacturing base for energetics, to use the uniqueness of AM to improve performance and enhance safety, and to reduce time in getting new energetic systems into the fleet.[19]

AM has not only found terrestrial uses but now resides in space also. The NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama, launched the first 3D printer to the International Space Station (ISS) in September 2014 to test plastics. The second 3D printer was delivered to the ISS in April 2016. In addition to literally printing in space, NASA–MSFC performs reverse engineering based on 3D scanning and AM combined as an integrated manufacturing process to reduce the design-to-manufacture development cycle time. At the NASA Jet Propulsion Laboratory in Pasadena, California a two-dimensional sensor was developed by the Innovative Advanced Concepts program. The sensor is essentially a transparent sheet of plastic with printed electronics that has been proposed to collect environmental data in space or in a planet's atmosphere.

AM in the Logistics and Sustainment Mission

The Air Force sustainment centers located at Tinker AFB, Oklahoma; Robins AFB, Georgia; and Hill AFB, Utah, provide depot maintenance and supply chain operations and management and installation support for the Air Force's most sophisticated weapons systems—from the most advanced aircraft to helicopters. The airpower sustainment mission is ripe for directly applying industry-matured AM capability into nearly every aspect of air logistics operations. However, before delving into specific examples, one must first consider what logistics and sustainment encompass. In a broad sense, *logistics* means having the right thing, at the right place, at the right time and includes procurement, distribution, maintenance, and replacement of materiel and personnel.[20] The DOD definition of *sustainment* includes the provision of logistics and personnel services required to maintain and prolong operations until there is successful mission accomplishment.[21]

In the future, basic logistics runs may be routinely redirected to supply materials to outposts for direct-part manufacturing in the field to meet urgent needs while saving time and money. One such futuristic scenario is captured in the Air Force Future Operating Concept. The goal is to air deliver a container of polymer for directly 3D printing parts at an isolated outpost. The file to print the needed part is sent via a secure space connection, while the airdrop delivery of materials is ultimately successful and the printer generates the critical part within hours compared to days, saving millions of dollars in the process.[22] Scenarios such as this generate great enthusiasm for AM due to the asymmetric advantage it offers national defense. There are many other examples of how AM is envisioned to innovate military logistics, sustainment, acquisitions, and weapons development. Embracing AM into the role of logistics and sustainment creates three opportunities:

- AM can be used to reverse engineer replacement parts for legacy aircraft that are no longer in inventory. Aircraft, such as the venerable B-52 Stratofortress, are aging and often need parts quickly that have not been manufactured for decades. Three-dimensional laser mapping and other techniques can be used to manufacture existing parts.
- Improve the design of existing parts before final parts are manufactured. Dr. Kristian Olivero at the Oklahoma City Air Logistics

Complex said, "Even if your final part is going to be machined, you can print it in plastic five times to make sure it's got the correct geometries, the right tolerances, the correct interfaces, and then machine the final one."[23]

- AM can reduce unnecessary parts purchases and reduce parts inventory by printing replacement parts on demand in the field. However, there is a learning curve to implement and manage this new process into depot maintenance. For example, replacement engine parts are currently purchased, shipped to the depot, stored in inventory, and pulled when needed. Instead, the parts could be printed on demand directly in the field or at repair and overhaul sites, thereby overcoming the need to deploy a range of spare components.[24]

The DOD Additive Manufacturing for Maintenance Operations Working Group (AMMO WG) is a great example of the DOD partnering with industry to:

> …develop an integrated DOD strategic vision and facilitate collaborative tactical implementation of AM technology in support of the DOD's global weapon system maintenance enterprise. The AMMO WG activity includes development of Office of the Secretary of Defense guidance recommendations, selection, and prioritization of opportunities to employ AM technology, coordination, and standardization of AM activities into established DOD maintenance processes and procedures and preparation and maintenance of the AMMO Roadmap.[25]

The National Center for Manufacturing Sciences (NCMS)—a private, nonprofit, technology-development consortium—provides industry leadership and participation from manufacturers across all industry sectors.

The AMRDEC, in collaboration with the Corpus Christi Army Depot, is also working to demonstrate the benefits of laser additive manufacturing technologies for the restoration, reclamation, and reutilization of high-value aviation assets located at the Storage, Analysis, Failure Evaluation, and Reclamation facility.[26] AM will be used to demonstrate repairs on Army aviation assets that cannot currently be restored to service using traditional manufacturing methods. Project objectives include improvement in acquisition lead times for component replacement, reduction in costs that negatively impact operations and support and operational readiness, and the establishment of qualified repair procedures for candidate parts.

Can AM Revolutionize the Acquisition Process?

Reducing the development cycle through highly streamlined and innovative approaches that ultimately accept risk in exchange for acquisition speed can address the mounting concerns about maintaining technical superiority.[27] In the realm of acquisitions, this form of agility could be called *process agility*. Attempts at process agility can be found in *acquisition reform*, where the goal was to merge science and technology and acquisitions and requirements more seamlessly to improve overall capability development. However, this process has not been successful and more recent efforts in the USAF focus on including more "pivot points," or opportunities to change or abandon a program, as well as more rapid prototyping to advance technology through exploring innovative operational concepts.[28] One could envision an acquisitions process reduced to its simplest form through AM by acquiring and fielding the printers, materials, and files responsible for printing vehicles and systems. If successful, this process could revolutionize the speed of the acquisition.

While designing new systems, we must also stay mindful that our adversaries are also modernizing and working to counter our technology, so it must be part of the development process to anticipate and plan for emerging threats.[29] One method to plan for technology insertion is the use of modular architectures, which consist of severable components that can be rapidly upgraded. Additively manufacturing relatively simple autonomous vehicles and systems at lower cost and with modular options presents strategic and operational opportunities for practicing agility in precision global-strike missions in highly contested environments. Many of these assets have incorporated modular platforms—consisting of sensors, decoys, electromagnetic jammers, and munitions—to produce lethal and nonlethal effects.[30] These expendable decoys or small unmanned vehicles provide flexibility by being deployable from any combination of surface, air, or space assets. Modularity also creates the potential for additional providers that could submit products for increased competition and the development of alternative options.[31]

While the purpose for setting up any process is to minimize variation and allow repeatability, sometimes the process becomes so involved we lose sight of the ultimate goal. For example, the qualification and certification process should be reviewed to determine if a more rapid utilization of AM products can be pursued. This could be one small step in eliminating the excessive development times for complex capability

systems (15–20 years). A shift in concepts from a "defined and finite" system, or component life, to "adequate," for a certain application and length of time, would also be beneficial for rapid technological advancements.[32] Certification should be approached based on the function and criticality of the AM part. Not all parts will need to undergo a rigorous qualifications process, as many parts could have an acceptable level of risk for the benefit of agility that AM brings. Similar to the benefits of modularity, the rapid fielding of additively manufactured, attritable, unmanned aerial vehicles (UAV) has the potential to reduce development time and save money while implementing new technology. Another example of incorporating AM for rapidly fielded technology is to reduce launch costs, which are currently a major factor facing USAF Space Command.[33]

It is worth mentioning the importance of having a strong linkage to early research and development discoveries while systems are being developed. Without this knowledge through connections to basic research, some technology insertion opportunities may be missed. However, with an awareness of the maturation of individual technologies, we can plan for periodic technology refresh in our acquisition plans while development is still in progress.[34] The lessons learned to date indicate that the US government needs to secure technical control and ownership of the relevant interfaces, including those required for software integration.[35]

A National Manufacturing Network

The incorporation of AM into defense is occurring in parallel with the establishment of a NNMI, originally proposed in 2012 by Pres. Barack Obama via a $1 billion addition to his fiscal year (FY) 2013 budget.[36] The vision for the NNMI is to set up a total of 15 institutes by FY 2024—shared between the government departments, including the DOD, Department of Energy (DOE), Department of Commerce (DOC), and the Department of Agriculture (DOA). As of 2015, a total of eight Institutes for Manufacturing Innovation have been established (five DOD and three DOE). The DOD institutes include the Additive Manufacturing Institute, also known as "American Makes," in Youngstown, Ohio; the Digital Manufacturing and Design Innovation Institute in Chicago, Illinois; the Lightweight and Modern Metals Institute, also known as Lightweight Innovations for Tomorrow, in Detroit, Michigan; the Institute for Integrated Photonics Manufacturing, also known as the American Insti-

tute for Manufacturing Integrated Photonics, in Rochester, New York; and the Flexible Hybrid Electronics Manufacturing Innovative Institute, also known as NextFlex, in San Jose, California.

The DOE's institutes are referred to as Clean Energy Manufacturing Innovative Institutes and include the Next Generation Power Electronics Manufacturing Innovative Institute, also known as "Power America," in Raleigh, North Carolina; the Advanced Composites and Structures Materials Manufacturing Institute, also known as the Institute for Advanced Composites Manufacturing Innovation, in Knoxville, Tennessee; and the Clean Energy/Smart Manufacturing Innovative Institute in Los Angeles, California.[37]

Seven new institutes were proposed for 2016 (one for the DOD, two for the DOE, two for the DOC, and two for the DOA)—worth a cumulative total of $608 million. The 2016 DOD-funded institute is the Revolutionary Fibers and Textiles Manufacturing Innovation Institute in Cambridge, Massachusetts. The DOE sought $241 million in 2016 to sustain its four existing institutes and set up two new institutes. The DOA requested $80 million to set up two institutes in the areas of advanced biomanufacturing and nanocellulosics. The DOC's National Institute of Standards and Technology requested the creation of up to two institutes in 2016, based upon any manufacturing topic area not previously selected.

The great diversity of research and development being performed by the National Manufacturing Innovative Institutes is influenced, in part, by military needs. The institutes are set up through both government funding and advisory committees consisting of academic, government, and industry members. For example, the AFRL feeds into the institutes by being engaged in the program reviews and technical working groups and through agency-directed projects.

Future Opportunities and Challenges

The majority of printed parts still rely on the deposition of materials layer by layer to generate 3D structures. However, new technologies and sectors of usage continue to emerge. The future of AM will surely witness an increase in available options, ranging from large companies offering high-throughput industrial printers to small start-ups demonstrating unique capabilities in niche applications. In 2016, the top extrusion and selective laser-sintering printer manufacturers, Stratasys and 3D

Systems, are competing with new computer-aided printing technology introduced by HP (multi jet fusion) and Carbon3D continuous liquid interface production. The main advantages of the new technologies include 10–100x faster print times compared to existing printers and improved surface finishes. The starting materials also play an integral role in overall improvements to product quality. Although acrylonitrile-butadiene-styrene (ABS) and polylactic acid (PLA) plastic filaments are still extensively used by many printers, the list of available materials is steadily growing, including custom-designed composites, glass, ceramics, and conductive inks. The implementation of AM is fostered by increased competition between emerging printer companies and material providers, but the cost of materials is still a concern for the mass adoption of AM. There are some discussions of using indigenous resources and assets such as recycled materials, especially for printing in remote locations where material delivery could be problematic.[38] Natural resources such as sands, clays, organic debris, and harvestable marine materials are also being considered as material options.[39]

The size of printed structures continuous to grow, including low-cost modular buildings in China, Italy, and here in the United States. The tailorable layer-by-layer construction of such large structures has been compared to the millennia old ancient pyramids, which were not only impressive in size but contained intricate internal passageways.[40] Although the size of these structures is quite impressive, for AM to be considered a revolutionary "game-changing technology," increases in functionality of the fundamental building block materials and printer configurations are envisioned to enable the most revolutionary military applications. Some initial work has demonstrated pick and place sensors into printed structures to "embed" functionality, which is one step toward more-advanced 3D printed devices. The materials to enable thermal and electrical conductivity for electronics (for example, traces, solders, and such) also are undergoing rapid development, taking advantage of the unique properties of nanoconstituents such as silver and carbon nanotubes. The formulation development has resulted in "inks" that exhibit shear thinning and are thereby suitable for the many commercially available 3D printers that use syringe-style printing as well as adaptations of commercial printers with multiple printheads for multimaterials printing.[41] These are important developments toward functional products that consist of several different materials deposited by a single system.

Government entities have a role in tech "push" to influence the direction of commercial innovations. Some examples of possible next-generation manufacturing technologies geared toward multidomain national defense strategies could include optimized 3D printing and embedding of electronic components, strain gauges, and other sensors within aerodynamic structures and war fighters' battle gear to monitor the environment, performance, and wear and offer redundancy in forms of communication.[42] Techniques such as topology optimization for seating to better accommodate ergonomics of female pilots could be based upon 3D printed seat prototypes, leading to more comfort and reduced accidents.[43] The seats, helmets, and other equipment could even be tailored to the individual to create a truly customized flight environment. With the advent of advanced materials and printer systems, we can also expect to see an increase in fully printed UAVs and robots that perform dangerous tasks.[44] Growth in the area of additively manufactured textiles lends itself to smart fabrics for biomonitoring in the military as well as alternatives to meal replacements through printing tailorable nutrition. The large-scale printing of structures, especially with indigenous materials, lends itself to applications in disaster relief and the rapid setup of military camps.

There remains the challenge of generating original 3D-printing designs from software that has traditionally been used for subtractive manufacturing. However, many companies are working to generate software that is truly additive in nature, starting from a blank slate versus a fully populated material block. Along with software development, the actual time required to produce original designs can be a limiting factor for rapid prototyping. One solution is to start from a scanned file of a similar object and then perform modifications. Alternatively, a database containing high resolution files could be accessed based upon a part number or a scanned object. Disney has filed such a patent on "object recognition for 3D printing," which takes advantage of a low-resolution scan to match and print the object from a high-resolution copy contained within a database.[45] If such technologies become widespread, the acquisitions process could be reduced to its simplest form and become much more agile and rapid via AM. For example, printers could be acquired and fielded along with the materials and files responsible for on-demand, in-the-field printing vehicles and systems.

One overarching challenge within government and military efforts is to effectively coordinate AM activities. There are mounting concerns that the highly bureaucratic nature of the national manufacturing institutes and a general lack of awareness and coordination between the entities involved are resulting in a piecemeal approach that duplicates efforts, magnifies costs, and suboptimizes the eventual benefits of AM.[46] As a remedy, a reorganization effort is proposed in the form of a disciplined but flexible governance structure for all AM activity, such as centralized AM leaders in the government departments whose role includes coordinating AM strategy and policy and issuing guidance to all departmental organizations planning to implement AM—from line units in the field to sustainment centers around the globe.[47] A specific suggestion to lead the reform and strategic vision from the Office of the Secretary of Defense—specifically the Office of Emerging Capability and Prototyping—has been offered as a solution.[48] Therefore, for any real forward momentum to occur, the push to reform the present structure of AM efforts to a more forward-thinking posture will need to occur in parallel with technological innovation.[49] Beyond capturing and furthering the vision presented in the high-level strategic USAF documents presented in this article, there is a real need for leaders to be able to cut through the hype and present the critical gaps and technical challenges to closing those gaps. What are the challenges currently being faced at the depot level for implementing AM? Additionally, what are the near-term payoffs in military applications compared to progress in the AM community as a whole?

Conclusion

To expand military strategic engagement in AM, the synergy between the diverse arrays of available materials, evolving printer technologies, and established programs—including the NNMI—should be leveraged to accomplish the vision set forth for long-term enterprise efforts. The goal of moving AM from form to function is already being demonstrated in efforts increasing functionality (for example, embedded sensors) with materials development—such as thermal/conductive inks—and more sophisticated printing capabilities like multimaterial printing. Using AM in ways that maximize strategic and operational agility provides decision makers with viable solutions for the multidomain challenges facing our country.[50] Incorporating AM has broad implications for lo-

gistics and sustainment due to its ability to rapidly field capabilities. The time and cost savings afforded by AM have the potential to revolutionize acquisitions and redefine system qualifications and certifications. Therefore, the opportunity to apply AM to increase the agility of the diverse, multidomain, defense mission set is one step in ensuring that the United States has the dominant capabilities to meet emerging national security threats. SSQ

Notes

1. Deborah Lee James and Mark A. Welsh III, *America's Air Force: A Call to the Future* (Washington, DC: Department of the Air Force, July 2014), http://permanent.access.gpo.gov/gpo52086/AF_30_Year_Strategy_2.pdf; and Deborah Lee James and Mark A. Welsh III, *USAF Strategic Master Plan* (Washington, DC: Department of the Air Force, May 2015), http://www.af.mil/Portals/1/documents/Force%20Management/Strategic_Master_Plan.pdf.

2. Deborah Lee James and Mark A. Welsh III, *Air Force Future Operating Concept: A View of the Air Force in 2035* (Washington, DC: Department of the Air Force, September 2015), http://www.af.mil/Portals/1/images/airpower/AFFOC.pdf.

3. The linkage is documented in several key US Air Force (USAF) reports and plans including the Office of the USAF Chief Scientist, *Global Horizons* (Washington, DC: Department of the Air Force, 3 July 2013); James and Welsh, *A Call to the Future*; Frank Kendall, *Better Buying Power 3.0*, US government white paper (Washington, DC: DOD, 19 September 2014), http://bbp.dau.mil/docs/2_Better_Buying_Power_3_0(19_September_2014).pdf; James and Welsh, *USAF Strategic Master Plan*; and James and Welsh, *Air Force Future Operating Concept*.

4. James and Welsh, *USAF Strategic Master Plan*.

5. The linkage is documented in several key US Air Force (USAF) reports and plans including the Office of the USAF Chief Scientist, *Global Horizons*); James and Welsh, *A Call to the Future*; Kendall, *Better Buying Power 3.0*; James and Welsh, *USAF Strategic Master Plan*; and James and Welsh, *Air Force Future Operating Concept*.

6. Ibid.

7. Office of the USAF Chief Scientist, *Global Horizons*.

8. Matthew J. Louis, Tom Seymour, and Jim Joyce, "3D Opportunity for the Department of Defense: Additive Manufacturing Fires Up," Deloitte University Press (web site), 20 November 2014, http://dupress.com/articles/additive-manufacturing-defense-3d-printing/.

9. These data are reported by the annual Wohlers Report, produced by Wohlers and Associates, which has been describing the industry and technology status of AM or 3D printing (used interchangeably) since 1996: https://www.wohlersassociates.com/state-of-the-industry-reports.html. This report has grown from an initial 40-page document to a 315-page document in 2015. It covers the history of 3D printing, processes and materials, system manufacturers, industry growth, global reports, direct part production, and research and development and provides a glimpse into the future.

10. Jon R. Drushal, "Additive Manufacturing: Implications to the Army Organic Industrial Base in 2030" (fellows paper, US Army War College, April 2013), http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA593246; Heidi Milkert,

"3D Systems Is Working with Marine Corps on a War Game Involving 3D Printing & Scanning," *3DPrint.com*, 25 August 2014, http://3dprint.com/12861/3d-systems-marines-3d-print/; Sean R. Walsh, "3D Printing: Enhancing Expeditionary Logistics," *Marine Corps Gazette* 99, no. 3 (March 2015), https://www.mca-marines.org/gazette/2015/03/3d-printing; and Julia Bergman, "Coast Guard Academy Professor Uses 3-D Printer on Arctic Icebreaker," *Military.com*, 28 September 2015, http://www.military.com/daily-news/2015/09/28/coast-guard-academy-professor-uses-3d-printer-board-arctic.html.

11. Adam Asclipiadis, "Rapid Equipping Force Uses 3D Printing on the Frontline," *Army Technology Magazine* 2, no. 4 (July/August 2014), https://www.army.mil/e2/c/downloads/353505.pdf; Jennifer McArdle, "Transforming Defense: The Potential Role of 3D Printing," *American Foreign Policy Council Defense Dossier*, February 2015, no.13, http://www.afpc.org/files/defense_dossier_february_2015.pdf; Meghann Myers, "Sailors Design Parts on Gators 3-D Printer," *Navy Times*, 18 May 2014; and Jordan Golson, "A Military-Grade Drone That Can Be Printed Anywhere," *Wired*, 16 September 2014, http://www.wired.com/2014/09/military-grade-drone-can-printed-anywhere/.

12. This work is supported through programs such as the Air Force Research Laboratory (AFRL), Commander's Research and Development Fund (CRDF), Flexible Electronics and General Ordnance Manufacturing (FLEGOMAN) program and through the Air Force Office of Scientific Research's (AFOSR) Integrated Circuits for Electronics in Extreme Environments (ICE3) Program. The ICE3 Program focused on the novel development of electrically conductive nanocomposite "inks," capable of being optimized to create layers of conductors, semiconductors, or resistors. See, John James, "AFRL Additive Manufacturing Program Advances Functional Prototyping," *Air Force Print News Today*, 13 January 2016, http://www.wpafb.af.mil/news/story_print.asp?id=123466848.

13. Audra Calloway, "3D Electronic Printing Holds Promise of Various Applications for Soldiers," *US Army News*, 2 December 2013, https://www.army.mil/article/116189/3D_electronic_printing.

14. Hayden K. Richards and David Liu, "Topology Optimization of Additively-Manufactured, Lattice-Reinforced Penetrating Warheads" (presentation, American Institute of Aeronautics and Astronautics SciTech Forum and Exposition, Kissimmee, Florida, 5–9 January 2015), http://www.i3dmfg.com/wp-content/uploads/2015/07/Richards-and-Liu-AM-warheads.pdf; Allison Dempsey, David Liu, Anthony Palazotto, and Rachel Abrahams, "Dynamic Properties of Additively Manufactured Stainless Steel" (presentation, American Institute of Aeronautics and Astronautics SciTech Forum and Exposition, San Diego, California, 4–8 January 2016), doi: 10.2514/6.2016-1510; and William T. Graves, David Liu, and Anthony N. Palazotto, "Topology Optimization of a Penetrating Warhead" (presentation, American Institute of Aeronautics and Astronautics SciTech Forum and Exposition, San Diego, California, 4–8 January 2016), doi: 10.2514/6.2016-1509.

15. Calloway "3D Electronic Printing Holds Promise."

16. Phillip Cullom, "5 Things to Know about Navy 3D Printing," *Navy Live* (blog), 15 July 2014, http://navylive.dodlive.mil/2014/07/15/5-things-to-know-about-navy-3d-printing/.

17. Sydney J. Freedberg Jr., "Warship Is Taking 3D Printer to Sea; Don't Expect a Revolution," *Breaking Defense News*, 22 August 2014, http://breakingdefense.com/2014/04/navy-carrier-is-taking-3d-printer-to-sea-dont-expect-a-revolution/.

18. Bryant Jordan, "Navy, Going Big on 3D Printing Next Year, Looking for Industry Ideas," *Defense Tech* (web site), 1 July 2015, http://www.defensetech.org/2015/07/01/navy-going-big-on-3d-printing-next-year-looking-for-industry-ideas/.

19. Naval Air Systems Command, "Energetic Materials Additive Manufacturing" (PowerPoint presentation, 2014), http://www.navair.navy.mil/osbp/index.cfm?fuseaction=home.download&id=597.

20. "What Is Logistics?," *Logistics World* (web site), 2016, http://www.logisticsworld.com/logistics.htm.

21. For the official definition of the US Department of Defense military term *sustainment*, see "U.S. DoD Terminology: Sustainment," *Military Factory* (web site), 2016, http://www.militaryfactory.com/dictionary/military-terms-defined.asp?term_id=5234.

22. James and Welsh, *Air Force Future Operating Concept*, 29.

23. John Parker, "Planning a Larger Role for 3-D Printing" *Tinker Air Force Base Public Affairs,* 19 October 2015, http://www.af.mil/News/ArticleDisplay/tabid/223/Article/624703/planning-a-larger-role-for-3-d-printing.aspx.

24. James and Welsh, *USAF Strategic Master Plan*.

25. Debra Lilu, *DoD Additive Manufacturing for Maintenance Operations (AMMO) Working Group Charter* (Ann Arbor, MI: Commercial Technologies for Maintenance Activities, May 2015), 20, http://www.ncms.org/wp-content/gallery/2015-CTMA-Partners-Meeting/CTMA_Program-2015-Digital.pdf.

26. US Army Manufacturing Technology (ManTech), "Additive Manufacturing to Restore/Reclaim/Reutilize High Value Aviation Assets," no date, http://www.armymantech.com/AMTRRRHVAA.php.

27. Kendall, "Better Buying Power 3.0."

28. Ibid.; and Joey Cheng, "Air Force's 30-Year Plan Seeks 'Strategic Agility'," *Defense Systems* (web site), 31 July 2014, https://defensesystems.com/articles/2014/07/31/air-force-30-year-strategy.aspx.

29. Kendall, "Better Buying Power 3.0."

30. James and Welsh, *Air Force Future Operating Concept*, 28.

31. Kendall, "Better Buying Power 3.0."

32. Office of the USAF Chief Scientist*, Global Horizons*.

33. Committee on Space-Based Additive Manufacturing, Aeronautics and Space Engineering Board, National Materials and Manufacturing Board, Division on Engineering and Physical Sciences, and National Research Council, "A Possible Way Forward for the Air Force," in *3D Printing in Space*, National Research Council (Washington, DC: National Academy of Sciences, 2014).

34. Kendall, "Better Buying Power 3.0."

35. Ibid.

36. Joel Hans, "Obama Asks Congress to Deploy Manufacturing 'Institutes,'" *Manufacturing.net* (web site) 13 February 2013, http://www.manufacturing.net/news/2013/02/obama-asks-congress-deploy-manufacturing-institutes.

37. White House, "President Obama Announces Winner of New Smart Manufacturing Innovation Institute and New Manufacturing Hub Competitions," White House, 20 June 2016, https://www.whitehouse.gov/the-press-office/2016/06/20/fact-sheet-president-obama-announces-winner-new-smart-manufacturing.

38. Committee on Space-Based Additive Manufacturing et al. "A Possible Way Forward."

39. Scott Cheney-Peters and Matthew Hipple, "Print Me a Cruiser!," *Proceedings* 139, no. 4 (April 2013).

40. Dale Brosius "Additive manufacturing: The Past, Present—and Future—of Composites," *Composites World* (web site), 31 July 2015, http://www.compositesworld.com/articles/additive-manufacturing-the-past-present-and-future-of-composites.

41. James O. Hardin, Thomas J. Ober, Alexander D. Valentine, and Jennifer A. Lewis, "Microfluidic Printheads for Multimaterial 3D Printing of Viscoelastic Inks," *Advanced Materials* 27, no. 21 (3 June 2015): 3279–84, doi: 10.1002/adma.201500222.

42. "Stereolithography Expedites Impeller Design," *Design News*, 7 September 1998, http://www.designnews.com/document.asp?doc_id=223384; and National Research Council, 3D Printing in Space, National Research Council (Washington, DC: National Academy of Sciences, 2014), 21.

43. Todd Rose, "When U.S. Air Force Discovered the Flaw of Averages," *Toronto Star*, 16 January 2016, http://www.thestar.com/news/insight/2016/01/16/when-us-air-force-discovered-the-flaw-of-averages.html; and Yolanda Nicole Andrade, "An Ergonomic Evaluation of Aircraft Pilot Seats" (Masters thesis, Embry-Riddle Aeronautical University, 2013).

44. Cheney-Peters and Hipple, "Print Me a Cruiser!"

45. Alec, "Disney Patent for 3D Scanning and High Resolution 3D Printing Approved by US Patent Office," *3ders.org* (web site), 22 February 2016, http://www.3ders.org/articles/20160222-disney-patent-for-3d-scanning-and-high-resolution-3d-printing-approved-by-us-patent-office.html.

46. Louis, Seymour, and Joyce, "3D Opportunities in the Department of Defense;" and McArdle, "Transforming Defense."

47. Ibid.

48. McArdle, "Transforming Defense."

49. Ibid.

50. Torri Ingalsbe, "Strategic Agility Is the Future of the Air Force," *Air Force Print News Today*, 30 July 2014, http://www.afmc.af.mil/news/story.asp?id=123419625.

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